Status and plans for the treatment of antibaryons in INCLXX,

…neutrinos, and uncertainties/errors

Jean-Christophe David

cea irfu

INFN
Istituto Nazionale di Fisica Nucleare
29th Geant4 Collaboration Meeting

07-11 October 2024 - Catania

Plan

- Antiprotons

- Antineutrons in INCL

- (light) Antinuclei in INCL

Bonus track

- Neutrino

- Uncertainties, errors (too early to discuss them, but…)

Why Antibaryons?

→ We have been asked to implement antiproton as projectile

- by people from AD (Cern) at rest (low energy - MeV)
  physics of anti-matter (% matter)
  new cross section measurements at ASACUSA

- by people from PANDA (FAIR) in-flight (higher energy - GeV)
  study of $\Lambda\bar{\Lambda}$ interaction

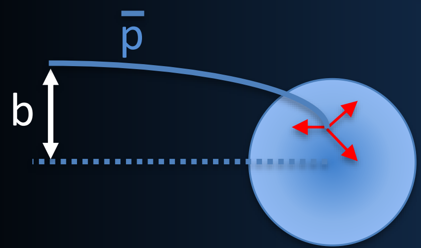
→ And the GAPS (*) experiment might be interested in $\bar{d}$, $\overline{^{3}\text{He}}$.

(*) The General AntiParticle Spectrometer (GAPS) aims to study dark matter through sensitive observations of cosmic-ray antiprotons, antideuterons, and antihelium.

Antiprotons

In-flight

$E_{at\ rest}$=200 MeV < E < 10 GeV

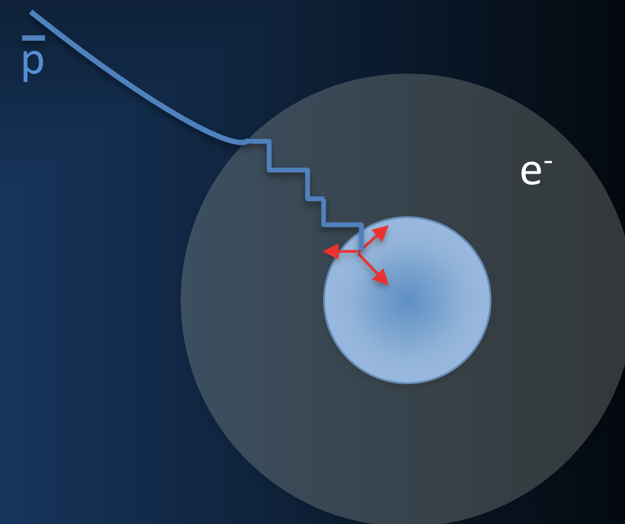


Main ingredients

- Cross sections
  - Elastic
  - Annihilation
  - Production
  - Charge exchange
- Final products (types; momenta)
- Potential ($\bar{p}$)

At rest

E < $E_{at\ rest}$= 200 MeV



Main ingredients

- Annihilation nucleon (p or n)
- Position of the Annihilation
- Final products (types; momenta)

Antiprotons
Results

In-flight
$E_{at\ rest}$=200 MeV < E < 10 GeV

Multiplicities

- Charged particles (total) ~OK
- Charged particles (w/ K^0) ~OK
- Charged particles (w/ Λ) To be improved

Spectra

- neutron OK

At rest
E < $E_{at\ rest}$= 200 MeV

Multiplicities

- $\pi^{+/-}$, n, α OK
- p ~underestimate
- d ~overestimate
- t, ^{3}He underestimate
- Kaon To be understood

Particle Spectra

- OK

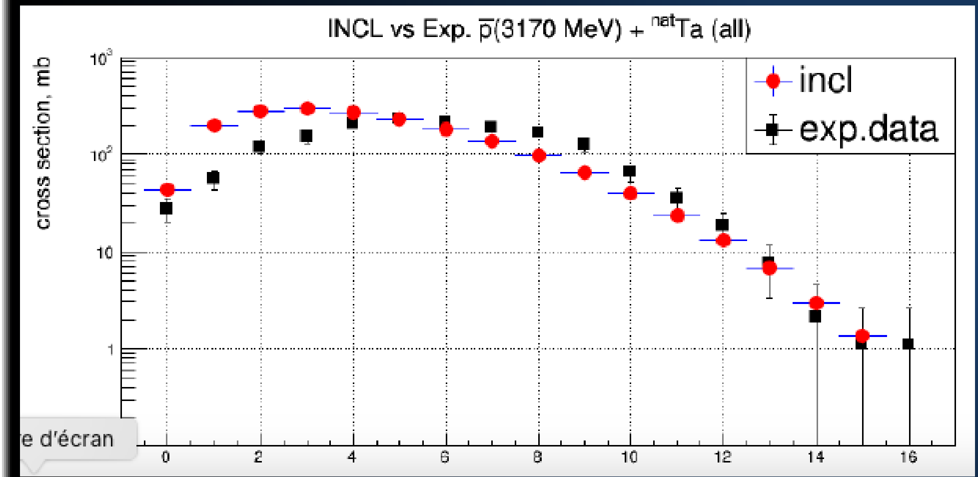
Residues

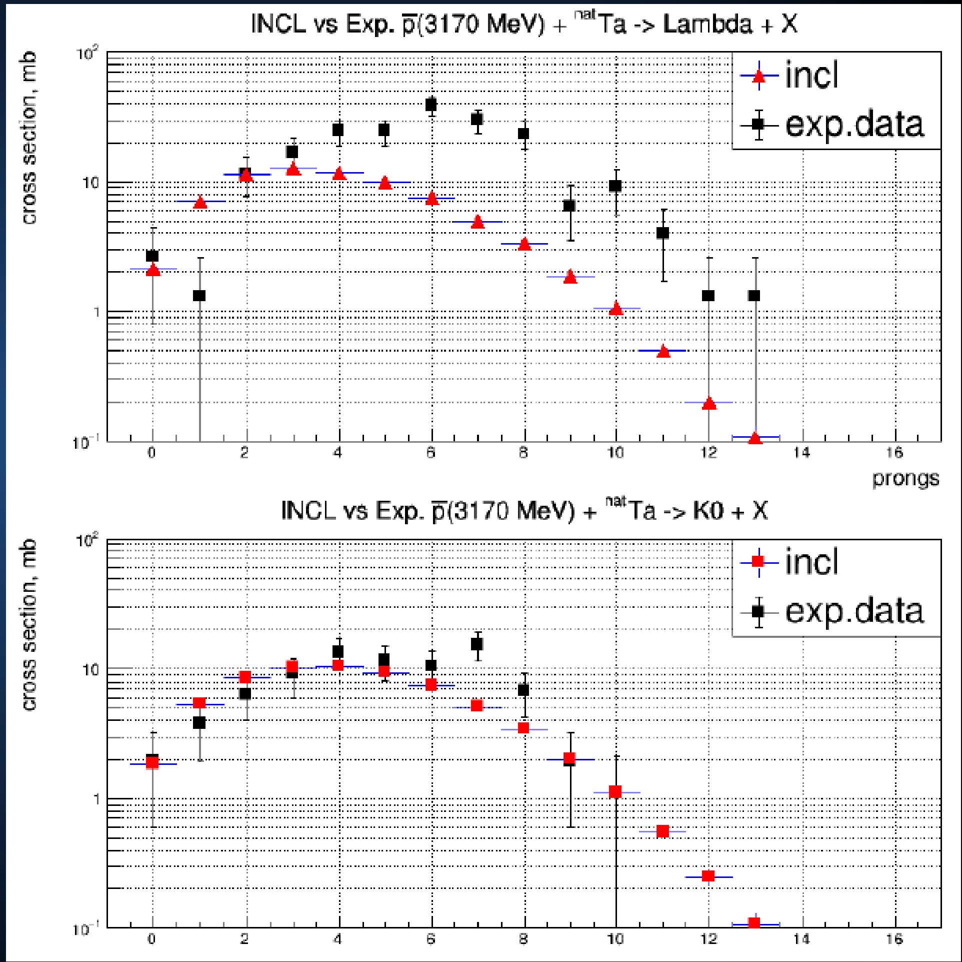
- OK

Antiprotons
Results

Multiplicities (charged particles)

$\bar{p}$ (4 GeV/c) + Ta





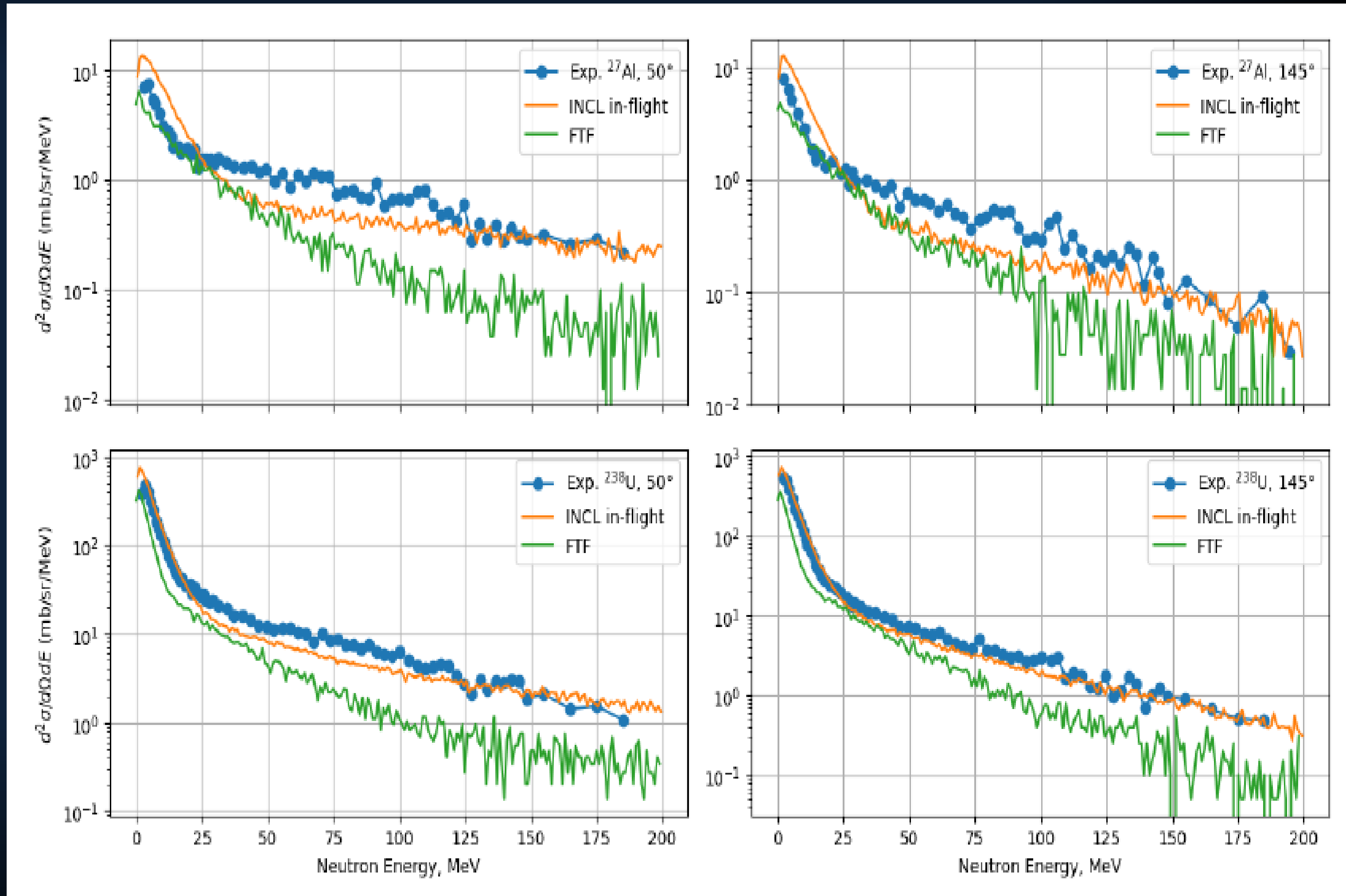
Antiprotons
Results

In-flight

Spectra (neutron)

$\bar{p}$ (1.22 GeV) + ^{27}Al

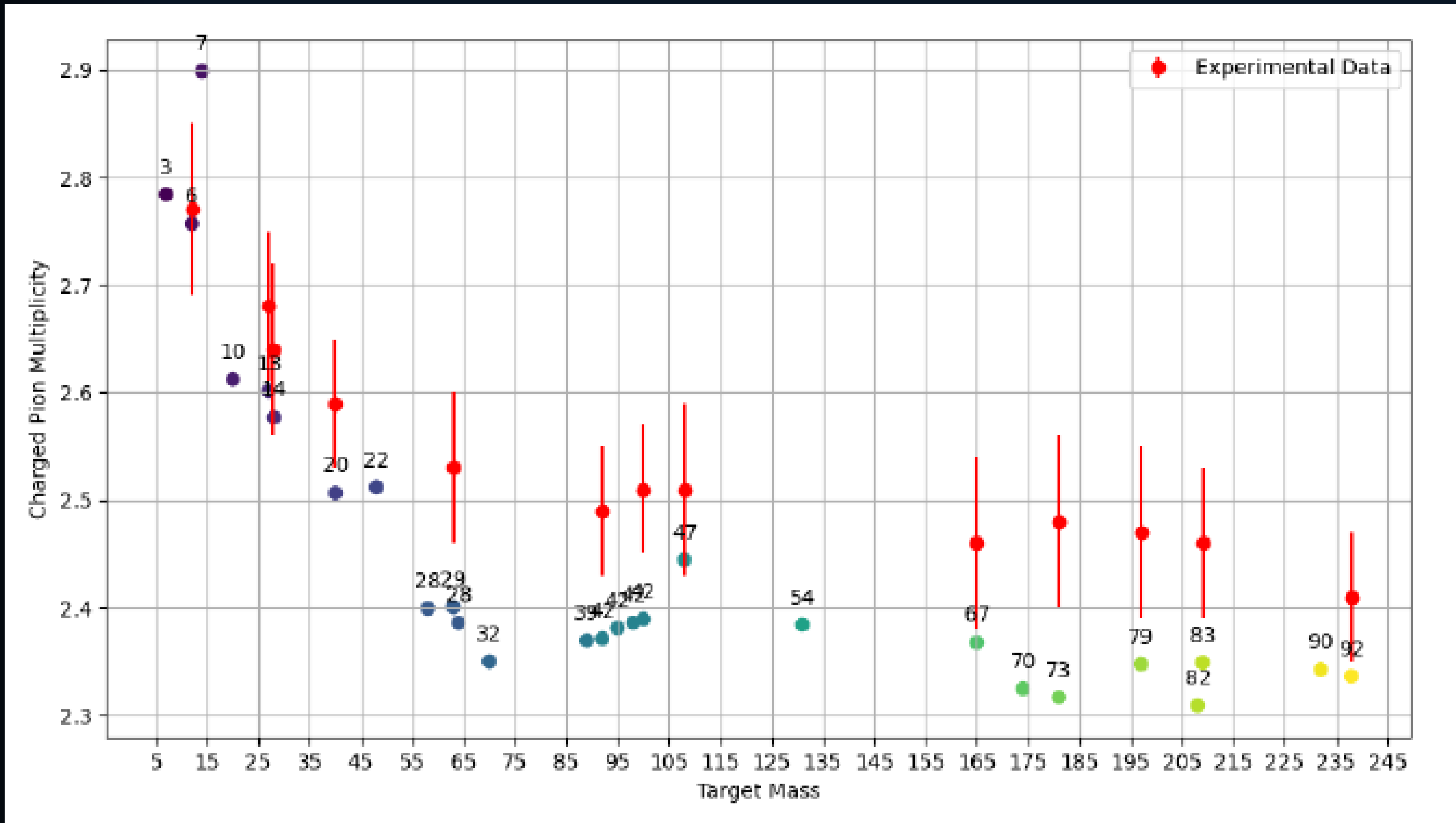
$\bar{p}$ (1.22 GeV) + ^{238}U



Antiprotons
Results

At rest

Multiplicities $\pi^{+/-}$



D. Polster et al. Phys. Rev. C51 (1995), 1167–1180.

Quite good, except a little too low multiplicities (4% too low)

→ Lack of information on annihilation with (very) high meson multiplicity…?

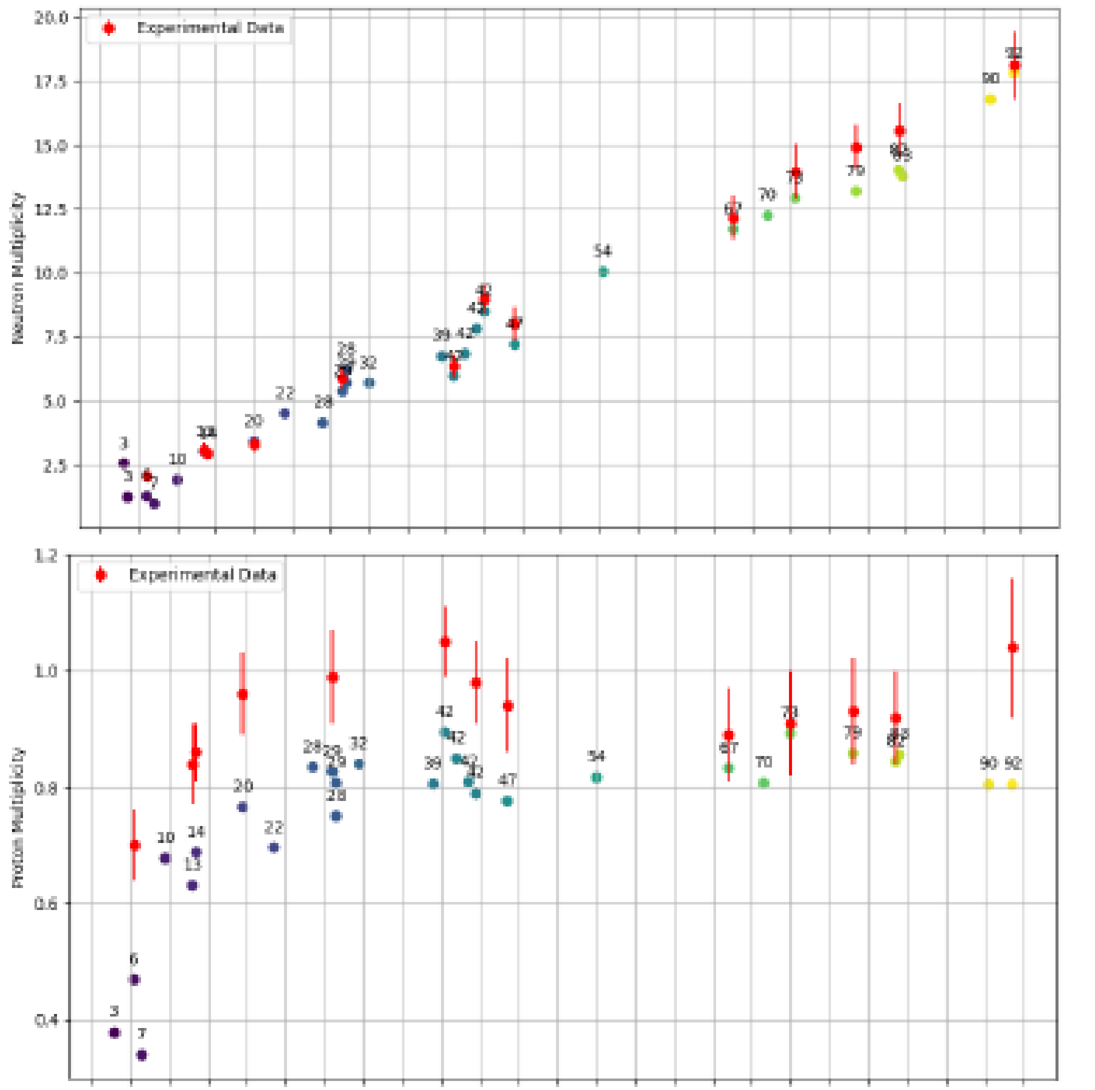
At rest

Antiprotons
Results

Multiplicities n & p

n

p

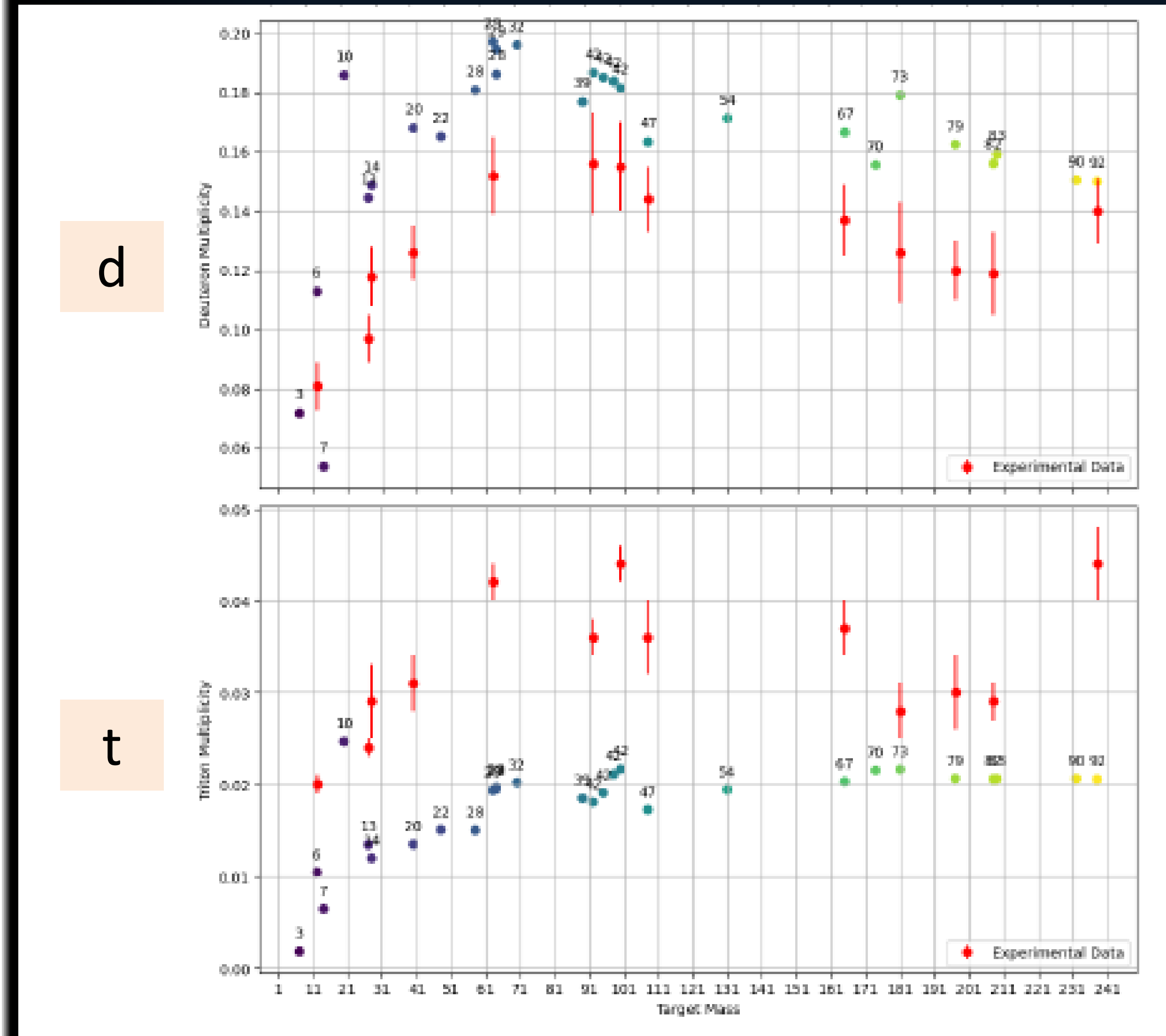


- n: ~perfect
- p: little underestimation (< 20%)

D. Polster et al.
Phys. Rev. C51 (1995),
1167–1180.

Antiprotons
Results

Multiplicities d & t



- d: overestimation (< 25%)
- t: underestimation (< x2)

D. Polster et al.
Phys. Rev. C51 (1995), 1167–1180.

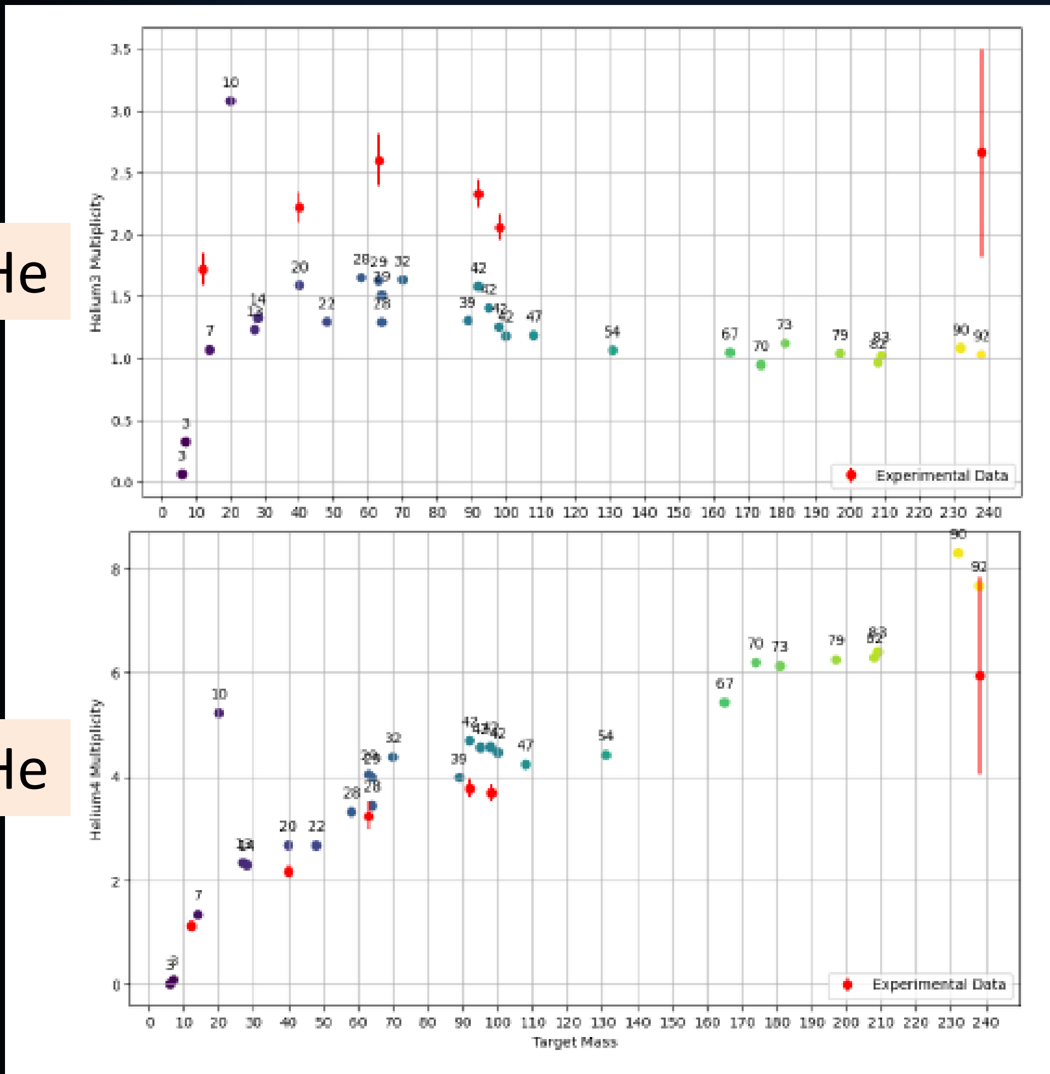
Antiprotons
Results

At rest

Multiplicities ^3He & ^4He

^3He

^4He



- ^3He: underestimation (< x1.5)
- ^4He: rather good

W. Markiel et al. Nuclear Physics A 485.3 (1988), 445–460.

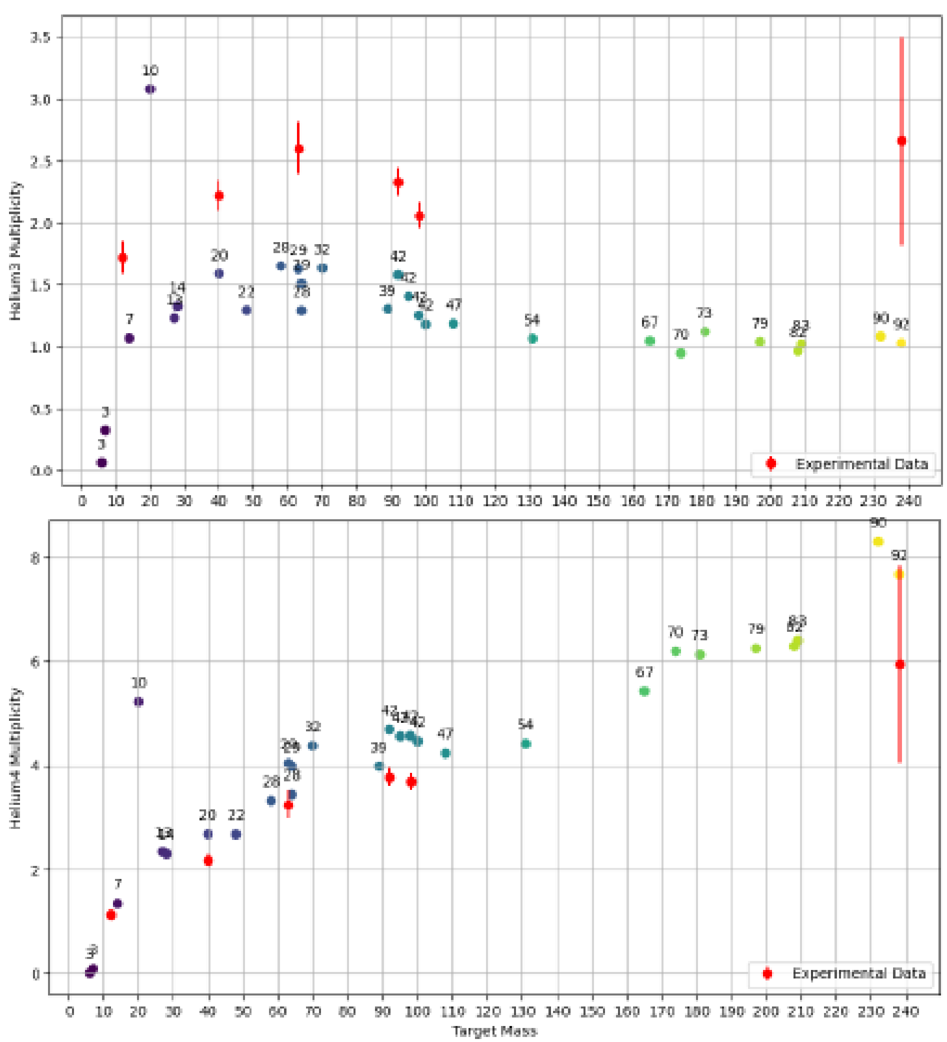
Antiprotons
Results

At rest

Multiplicities ^3He & ^4He

^3He

^4He



- ^3He: underestimation (< x1.5)
- ^4He: rather good

Here for given kinetic ranges…

INC (→ Coalescence model?)

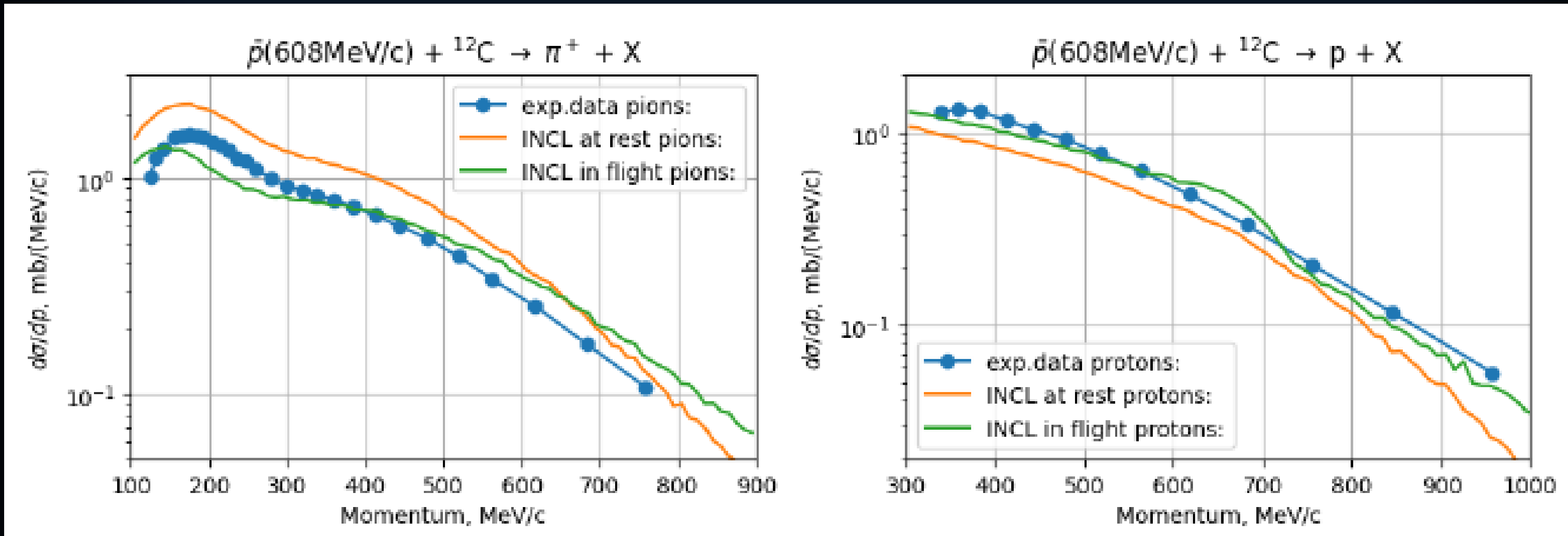
Deexcitation?

W. Markiel et al. Nuclear Physics A 485.3 (1988), 445–460.

Antiprotons
Results

At rest

Spectra π^+ & p



P. L. McGaughey et al., Phys. Rev. Lett. 56 (1986), 2156–2159.

Shape ~OK

π overestimate = artefact (INCL σ_{reac} too high here)
p underestimate as previously seen

Antiprotons
Results

At rest

Residue production

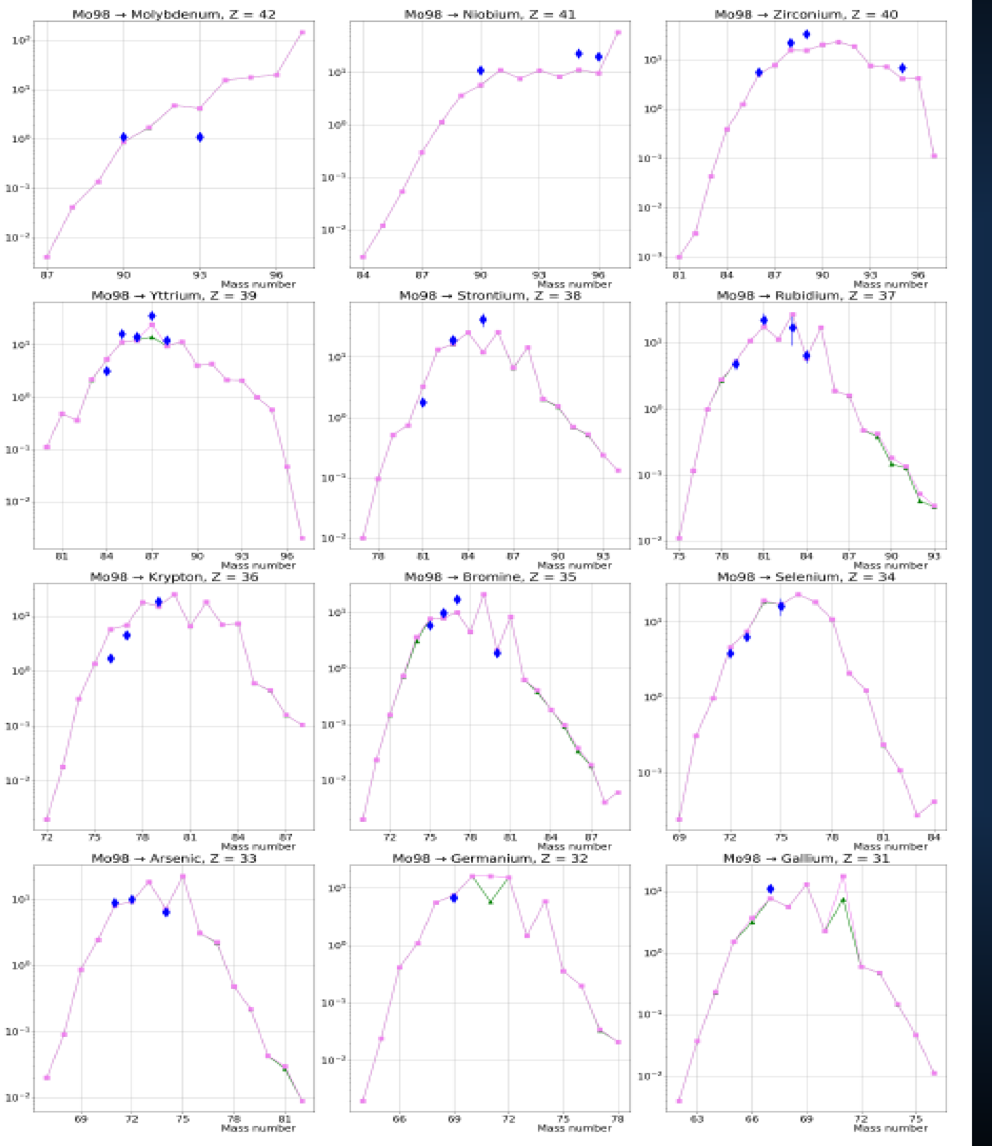


Figure 5.21: Cumulative isotopic distributions from the reaction $\bar{p}+^{98}Mo$. Calculated results are in violet (option $\frac{\lambda_{\bar{p}}}{\lambda_P} = 0.1$), and in green (option $\frac{\lambda_{\bar{p}}}{\lambda_P} = 0.5$). Definition of $\frac{\lambda_{\bar{p}}}{\lambda_P}$ in section 5.3.3.1. Data are from [Mos+89].

Here, cumulative production (progenitors accounted for)

Not bad at all, is it?

(same reliabilty as in p + A)

Mass distributions

$\bar{p} + {}^{98}Mo \rightarrow Z$

E. F. Moser et al.,
Z. Phys.A –
AtomicNuclei 333, 89-105 (1989)

Antiprotons
Status

- In Geant4 (since Geant4-11.2)

- Rather good results,
  but place to improvements
  - π high multiplicities (refinement)
  - p ~underestiamted
  - d overestimated; t and ^{3}He underestimated

    } new data from AD (ASACUSA) expected soon…
  - K K^0 ~OK
    $K^{+/-}$ underestimated
  - Λ undestimated

- Some not-so-well-known ingredients …
  (potential, position of the annihilation, on which nucleon (n? p?) the annihilation…)

Antineutrons

Beyond ~500 MeV/c $\bar{n}$ = $\bar{p}$

Below

$\bar{p}$ captured by electrons

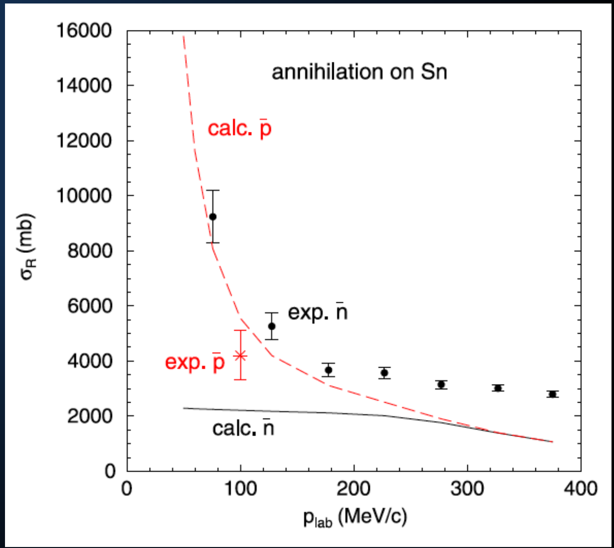
$\bar{n}$ should not be…

But

Exp. data exist only down to 100 MeV/c → Below, extrapolation is bad!

And…

From E. Friedman / Nuclear Physics A 925 (2014) 141–149



So

0 → 165 MeV/c force annihilation

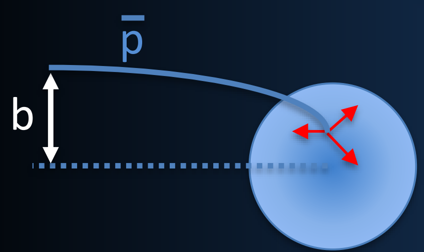
165 MeV/c → 500 MeV/c fit ($\bar{n}$) ≠ fit ($\bar{p}$)

500 MeV/c → … $\bar{n}$ = $\bar{p}$

Antiprotons

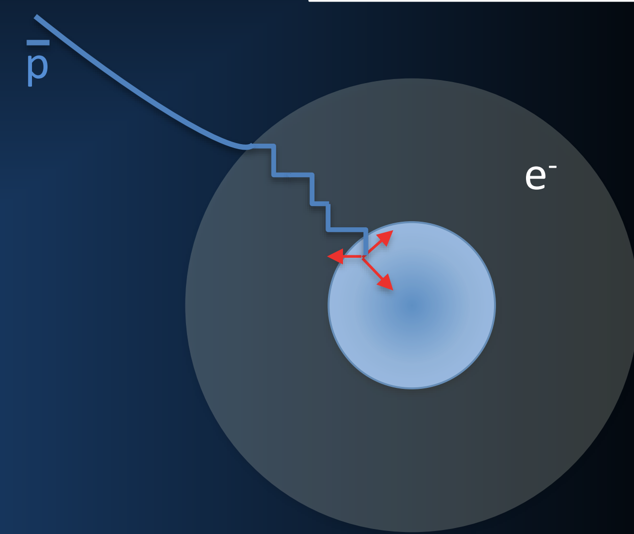
In-flight

$E_{at\ rest}$=200 MeV < E < 10 GeV



At rest

E < $E_{at\ rest}$= 200 MeV



Main ingredients

- Cross sections
  - Elastic
  - Annihilation
  - Production
  - Charge exchange
- Final products (types; momenta)
- Potential ($\bar{p}$)

Main ingredients

- Annihilation nucleon (p or n)
- Position of the Annihilation

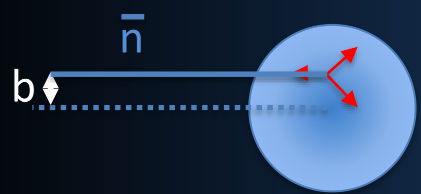
(overlap: wave function($\bar{p}$) x nucleon density)

- Final products (types; momenta)

Antineutrons

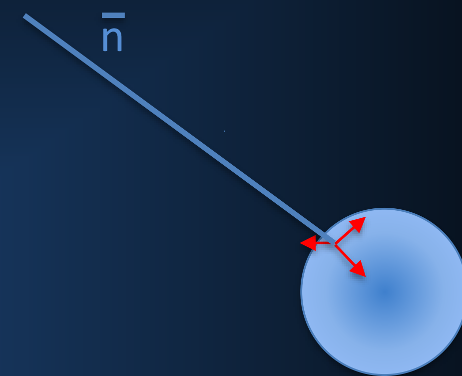
In-flight

$E_{at\ rest} = 14\ MeV < E < 10\ GeV$



« At rest »

$E < E_{at\ rest} = 14\ MeV$



<u>Main ingredients</u>

- Cross sections
  - Elastic
  - Annihilation
  - Production
  - Charge exchange
- Final products (types; momenta)
- Potential ($\bar{n}$)

<u>Main ingredients</u>

- Annihilation nucleon (p or n)
- Position of the Annihilation

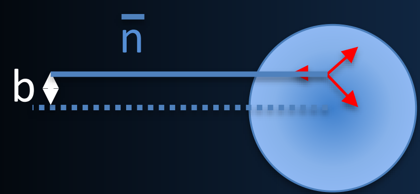
(approximated by a gaussian)

- Final products (types; momenta)

Antineutrons

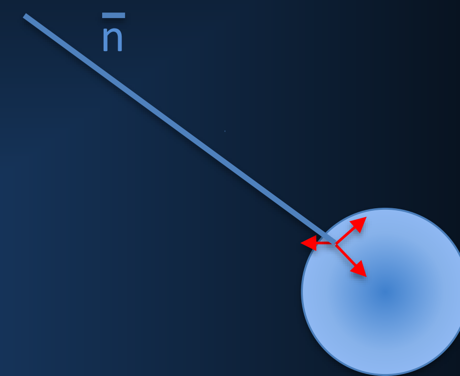
In-flight

$E_{at\ rest}$=14 MeV < E < 10 GeV

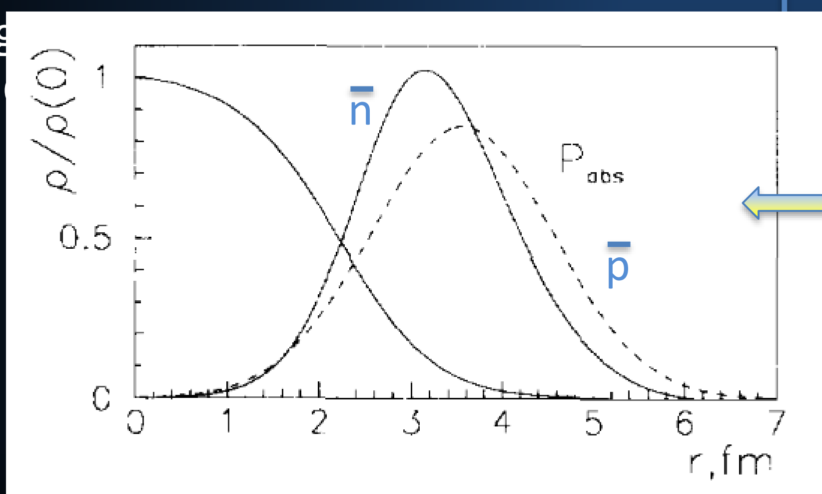


« At rest »

E < $E_{at\ rest}$= 14 MeV



Main ing



Main ingredients

- Annihilation nucleon (p or n)
- Position of the Annihilation

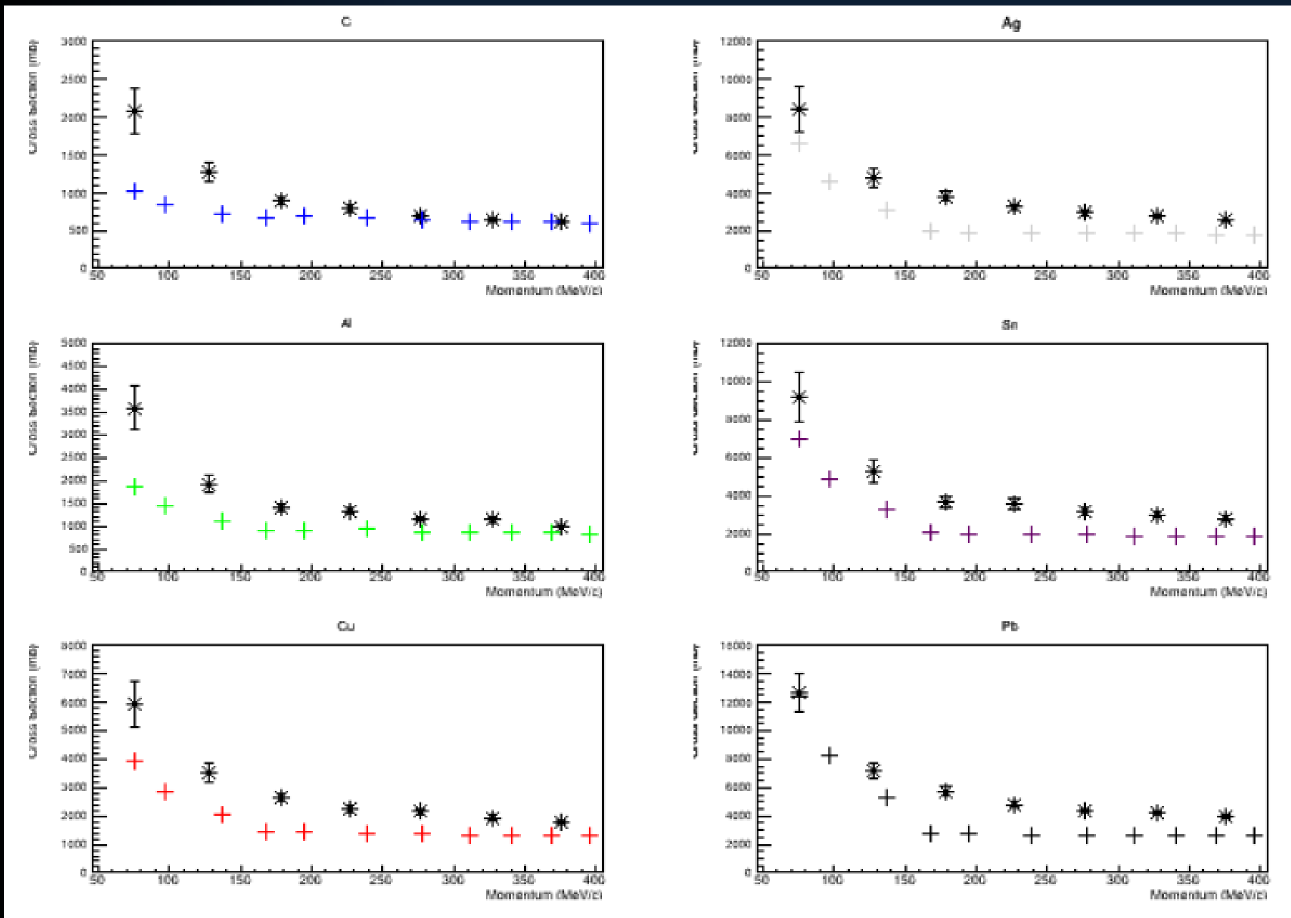
(approximated by a gaussian)

- Final products (types; momenta)

From E. S. Golubeva and L. A. Kondratyuk, Nucl. Phys. B56, 103 (1997).

Antineutrons
Results

Annihilation σ

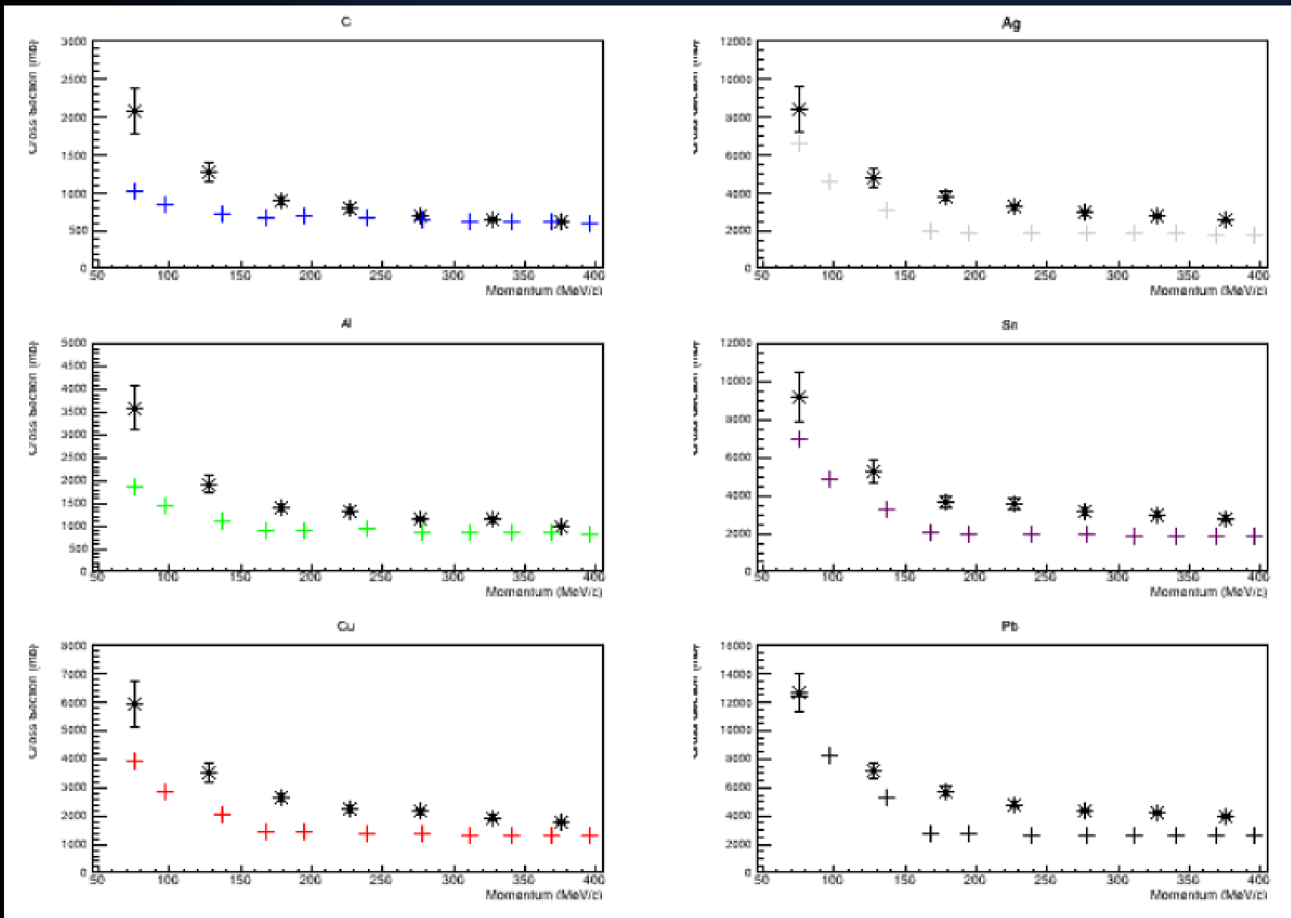


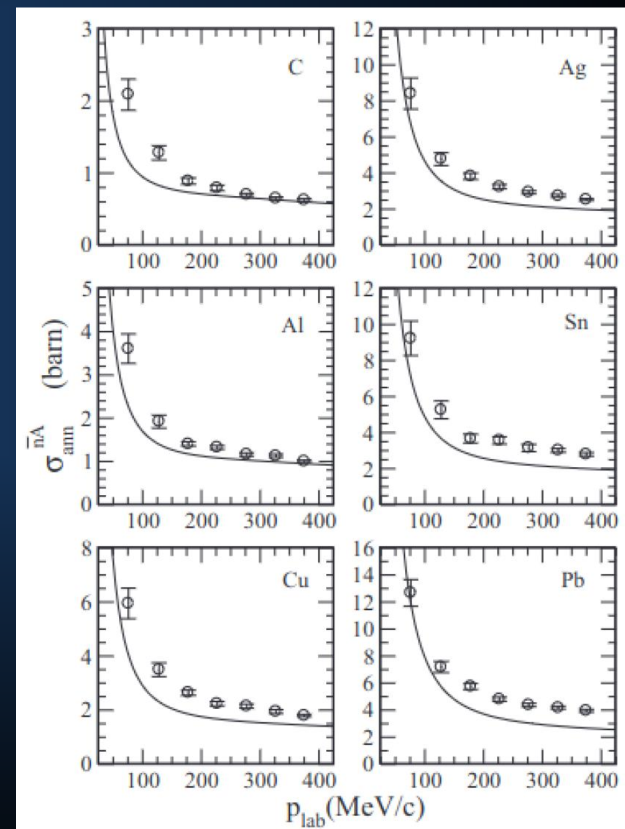
- Underestimation
- Depending on
  - the target
  - the energy
- But encouraging

Antineutrons
Results

Annihilation σ

- Underestimation
- Depending on
    - the target
    - the energy
- But encouraging
- …and similar to other model



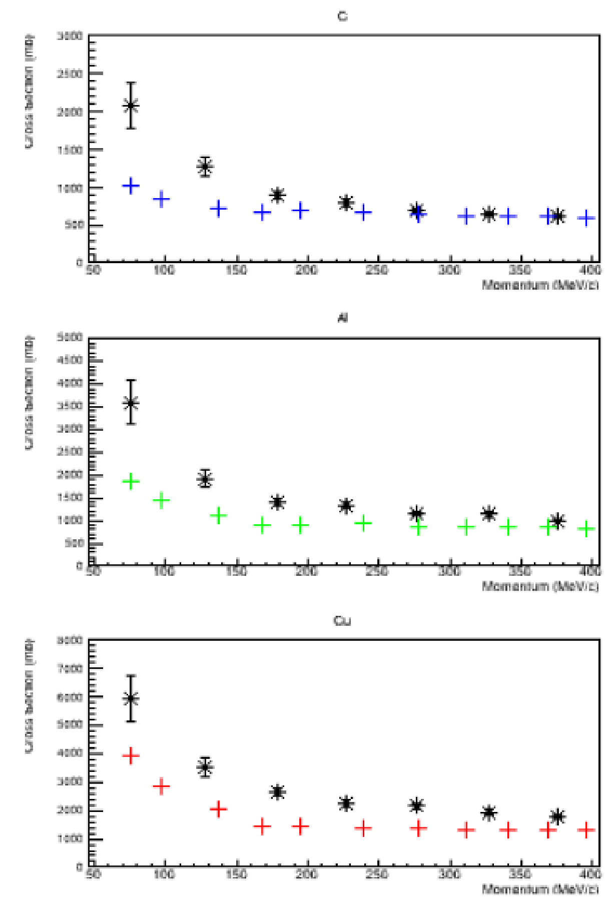


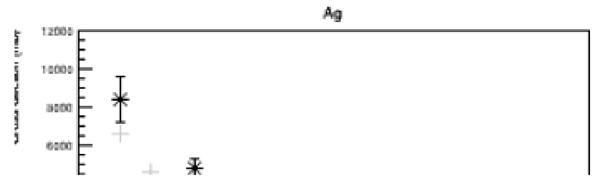
Lee and Wong. Phys. Rev. C 93, p. 014616 (2016)

Antineutrons
Results

Annihilation σ

- Underestimation
- Depending on
  - the target
  - the energy
- But encouraging
- …and even better at higher energy





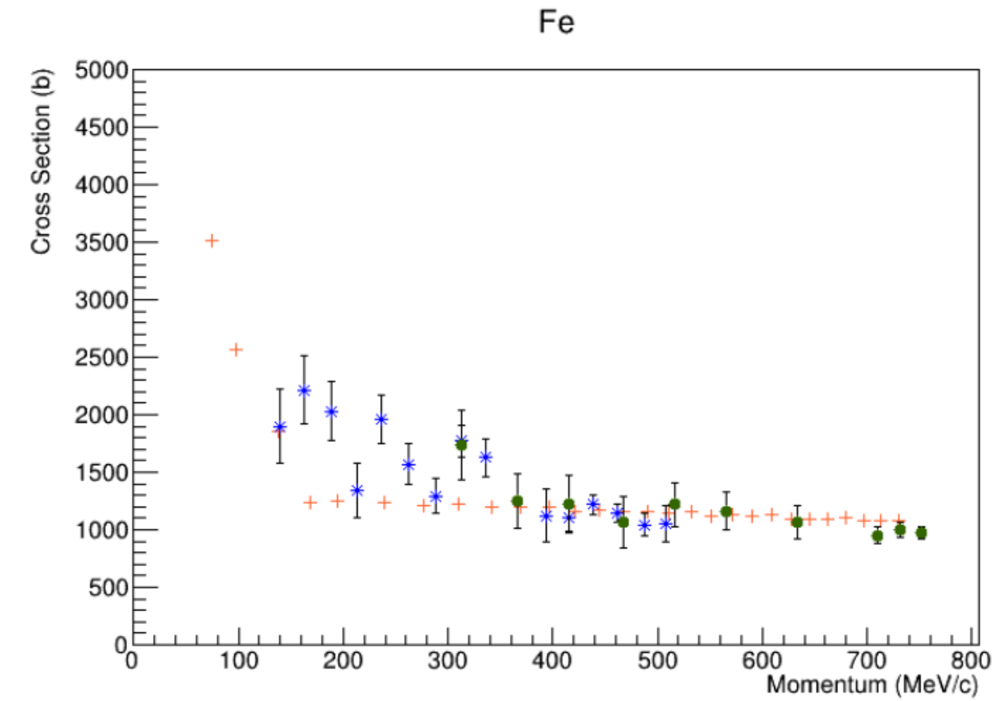


Figure 29: Sections efficaces finales du Fer. Potentiel : 50 MeV, Seuil "Au repos" : 14 MeV. Points bleus et verts : Données expérimentales de Ref. [34]. Points oranges : Données en sortie d'INCL.

Antineutrons
Results

Pion multiplicity

antineutron (750 MeV) on a target made of

	% of Target
H1	66.8 %
C12	26.6 %
F19	5 %
Br80	1.6 %
Total (INCL)	100 %
Total (Litt)	100 %

	% of Target	π^-	$\pi^+ + \pi^-$
Total (INCL)	100 %	0.98	2.73
Total (Litt)	100 %	1.23 ± 0.04	2.82 ± 0.07

- $\pi^+ + \pi^-$ OK
- π^- a little too low

- Well well well…

Antineutrons
Status

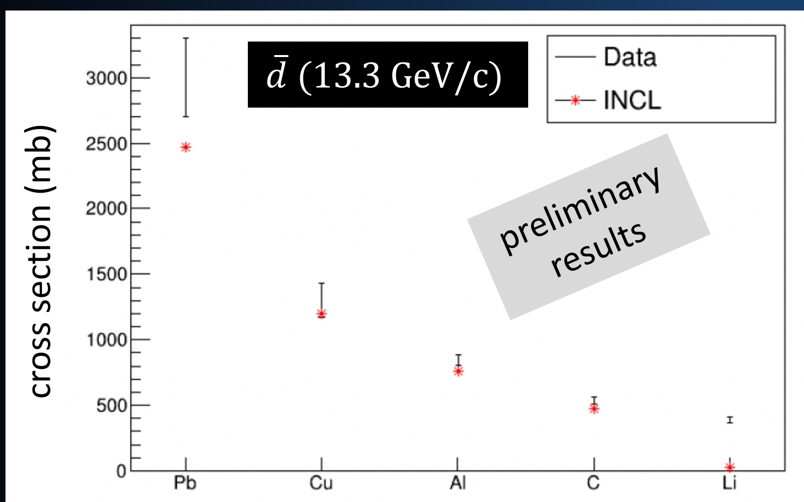
- Probably not in Geant4 this year (some checks)
- Results comparable to others
- As with antiprotons, some not-so-well-known ingredients …
  (potential, position of the annihilation, on which nucleon (n? p?) the annihilation…)

$\bar{d}, \bar{t}, \overline{^{3}He}, \overline{^{4}He}$

- INCL treats d, t, ^{3}He, ^{4}He-induced reactions (and more)
- Now $\bar{n}$ and $\bar{p}$-induced reactions available
- So, why not $\bar{d}$, $\bar{t}$, $\overline{^{3}He}$, $\overline{^{4}He}$ -induced reactions?

It's in progress… but at an (very) early stage with antideuteron!

First results are encouraging.



S.P. Denisov et al., Nuclear Physics B 31.2 (1971), pp. 253–260.

preliminary results

$\bar{d}$(6.1 GeV/c per nucleon) + Ta multiplicity

	π^{+}/π^{-}	p
Exp.	5.08 ± 0.08	7.26 ± 0.16
INCL	4.98	3.43
bias	0.04%	51.7%

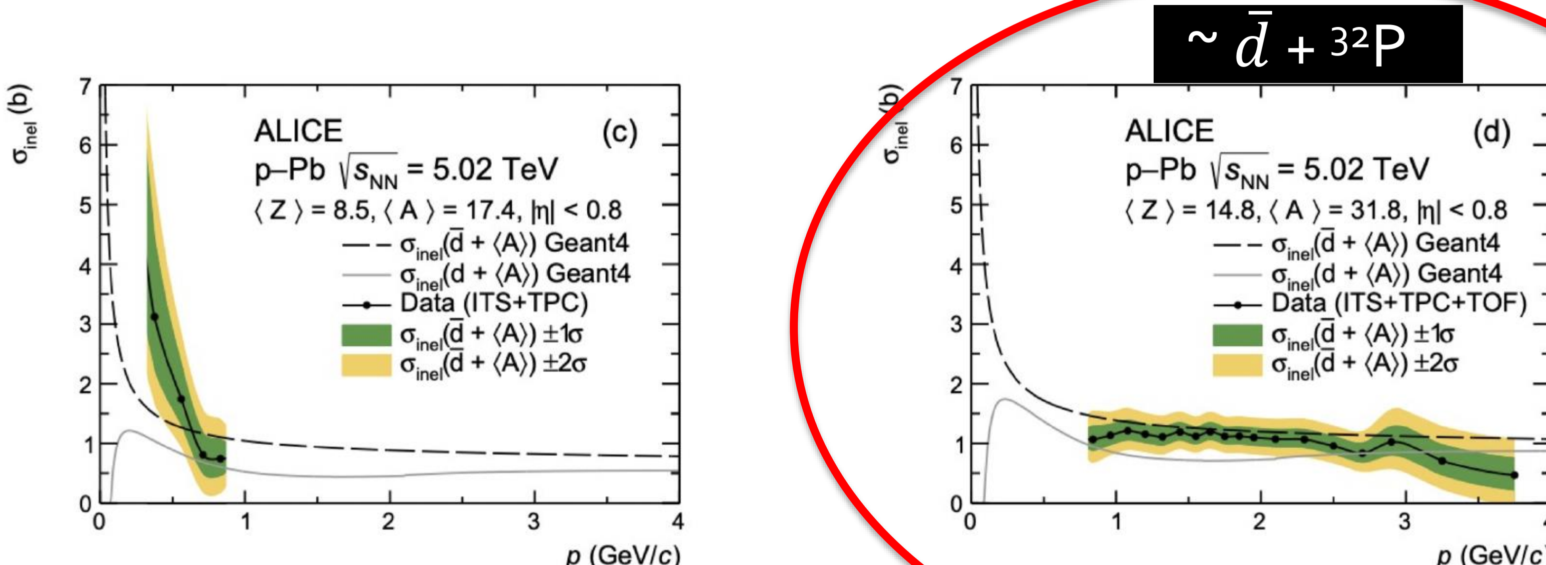
V. F. Andreyev et al.,
Il Nuovo Cimento A 103.8 (1990), pp. 1163–1176

$\bar{d}$, $\bar{t}$, $\overline{^{3}He}$, $\overline{^{4}He}$

From talk of Marilena (Monday)

ALICE requirement UR-59

- [1] Antideuteron inelastic c.s. (relevant results: Fig. 3 (c) and (d))
- https://inspirehep.net/literature/1797442
- HEP data (tables 13-16): https://www.hepdata.net/record/ins1797442



Contact:
Ivan Vorobyev: ivan.vorobyev@cern.ch

$\bar{d}, \bar{t}, \overline{^3He}, \overline{^4He}$

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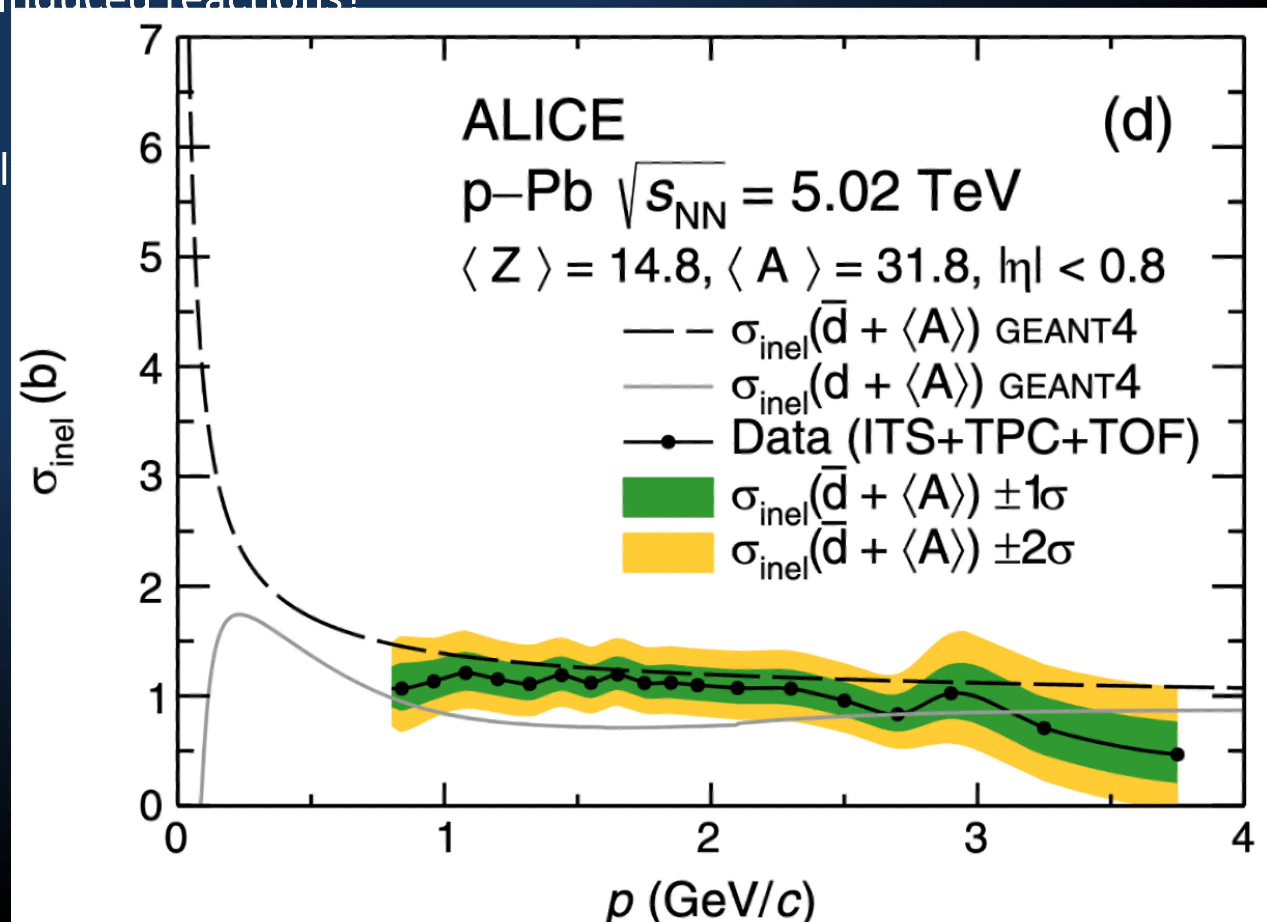

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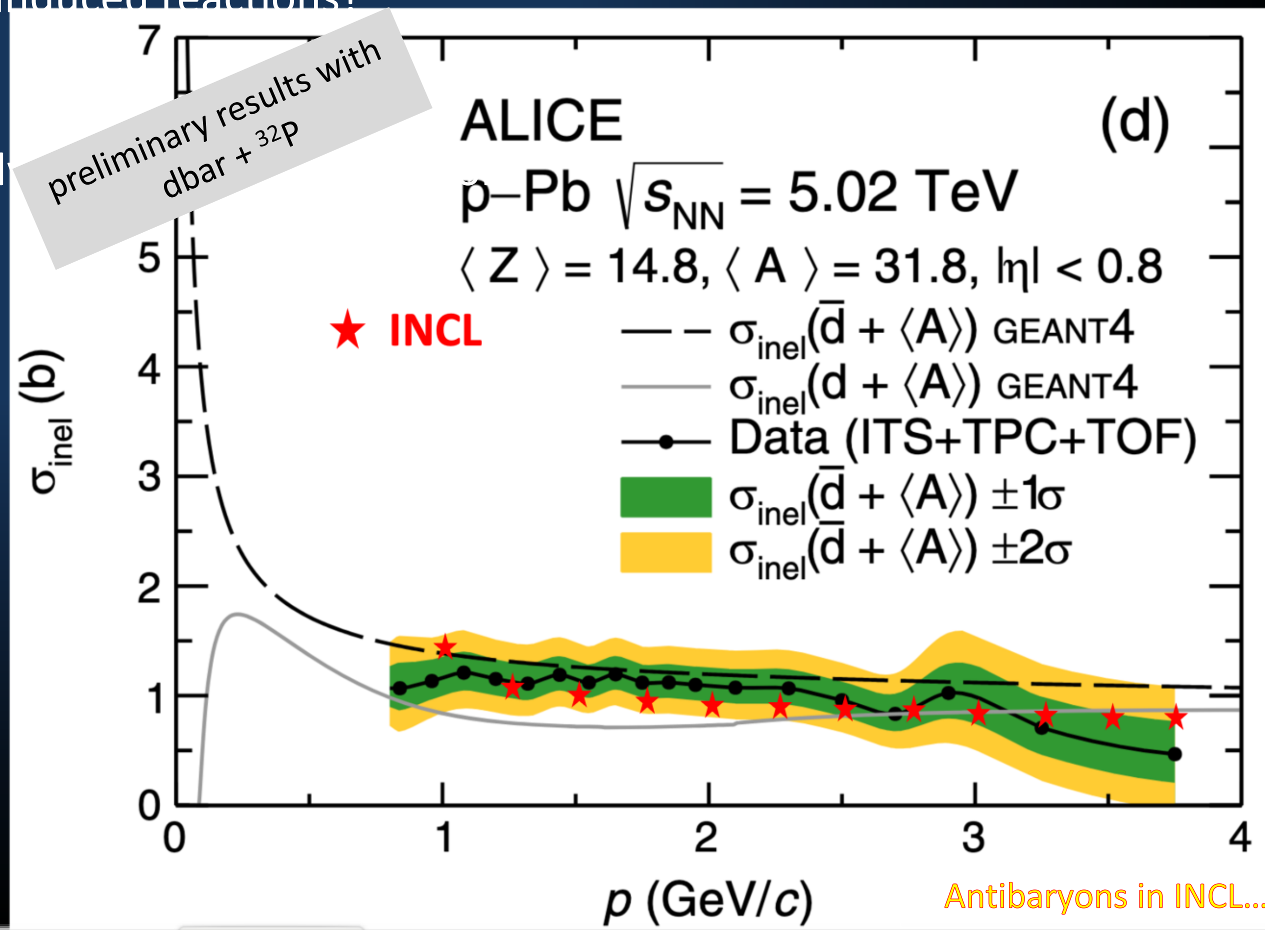


Just for informations…

(linked to Geant4 on the medium and long term)

Neutrinos

In some neutrino experiments,
Energy of the neutrino is known thanks to ν-Nucleus interaction products
BUT
Increasing precision of the experiments means better/refined results in ν-Nucleus interactions
Then
Need to use models known to treat well Final State Interaction (FSI)

Reminder (several type of interactions)

QE (CCQE – NCQE)	Quasi-elastic (Charge/Neutral Current)
RES	Resonant (Δ)
DIS	Deep Inelastic Scatering (higher resonances)

<u>Consequences for INCL</u>

	2019	2020-2023	2024	2024	2024
Who	**GENIE**	A. Ershova (Thesis **CEA**)	Antoine L.T. Internship (**CEA**)	**GENIE**	**NEUT**
Link/Goal	Contact	ν-oscillation exp. INCL to treat FSI	CCQE in INCL	New contact	Contact
Work	Implementing INCL	**NuWro** ν-N INCL FSI	It works Some points to be understood	Implementation OK? Used within Geant4?	Implementing INCL

Uncertainties, errors

- At the 23rd Geant4 Collaboration Meeting (2018 in Lund)
  - A presentation on the optimization of parameter thanks to Bayesian statistics…
  - Also the idea to determine the bias (error) of the model
- Difficulties
  - Building the tools
  - From the stand-alone model to the use in Geant4
- Status for INCL
  - A project (NuRBS: Nuclear Reaction model improvement with Bayesian Statistics) has been funded (2024->2027) – CEA & Bern U. (and IAEA+Coruña U.)
  - Goals:
    - Building tools for biasing and parameter optimisation
    - Applying them to INCL and ABLA for several cases
- Next steps propagate errors in Geant4…?

anr agence nationale de la recherche

Projet-ANR-23-CE31-0008

Conclusions

- Antiprotons
  - In Geant4 (since Geant4-11.2)
  - room for improvements
  - Some not-so-well-known ingredients → Nurbs project could help
- Antineutrons
  - Not yet in Geant4 (almost ready, but some checks are necessary)
  - Improvements (see antiprotons)
- Antideuterons and heavier
  - Work has started only… (but encouraging)

Thanks for your attention!

And thanks to the students

D. Zharenov (antiprorons + antineutrons)
O. Lourgo (antineutrons + antideuterons)
A. Ershova (neutrino in INCL using NuWro)
A. Legendre-Terrolle (neutrino CCQE in INCL)

and

J. Hirtz who gave advices

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *800945* — NUMERICS — H2020-MSCA-COFUND-2017

Backup

References

- Antiproton

  Most of the work presented here come from the thesis of Demid Zharenov, where all references are available (exp. data, input ingredients, etc.)

  https://theses.hal.science/tel-04511526

- Neutrino

  Thesis of of Anna Ershova

  https://theses.hal.science/tel-04267631

Antiprotons in INCL
Hypotheses – ingredients

At rest - Choice of nucleon to annihilate

We know

More on proton than neutron

Group	S_p/S_n
Rome-Syracuse[Bar+64]	1.31 ± 0.03
Berkeley[CK66]	1.33 ± 0.07
Padova-Pisa[Bet+67]	1.45 ± 0.07

And, for a same experiment

$S_p/S_n(D_2)$ between 57 and 170 MeV can range between 1.113 and 1.369

We use

$$S_p/S_n(D_2) = 1.331$$

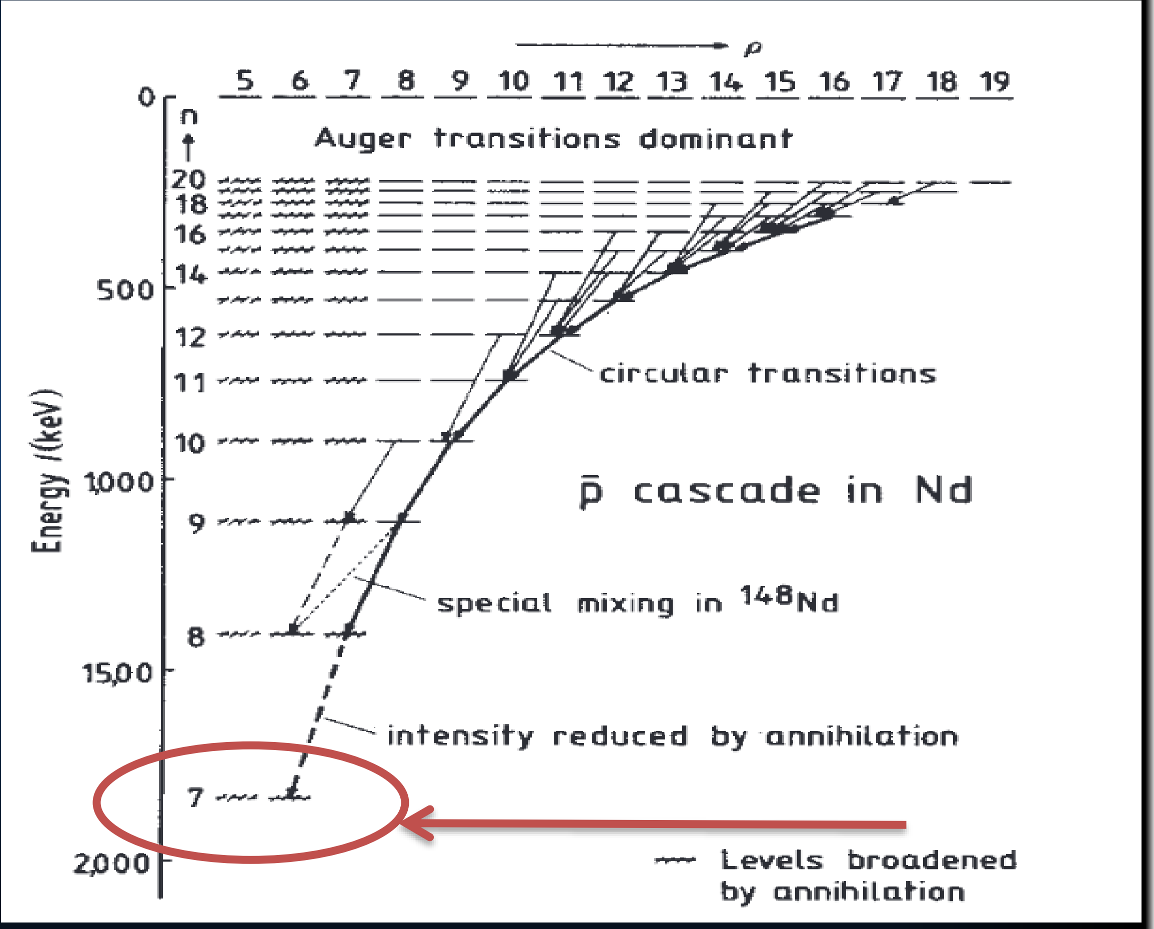
R. Bizzarri
Il Nuovo Cimento A (1965-1970) 53.4 (Feb. 1968), pp. 956–968

$$S_p/S_n(Z,A) = S_p/S_n(D_2)\frac{Z}{A-Z}$$

Antiprotons in INCL
Hypotheses – ingredients

At rest - Position of annihilation

- pbar
  Captured in a high Bohr orbit
  Cascades toward the nucleus
  Stops/annihilates at a given « n »

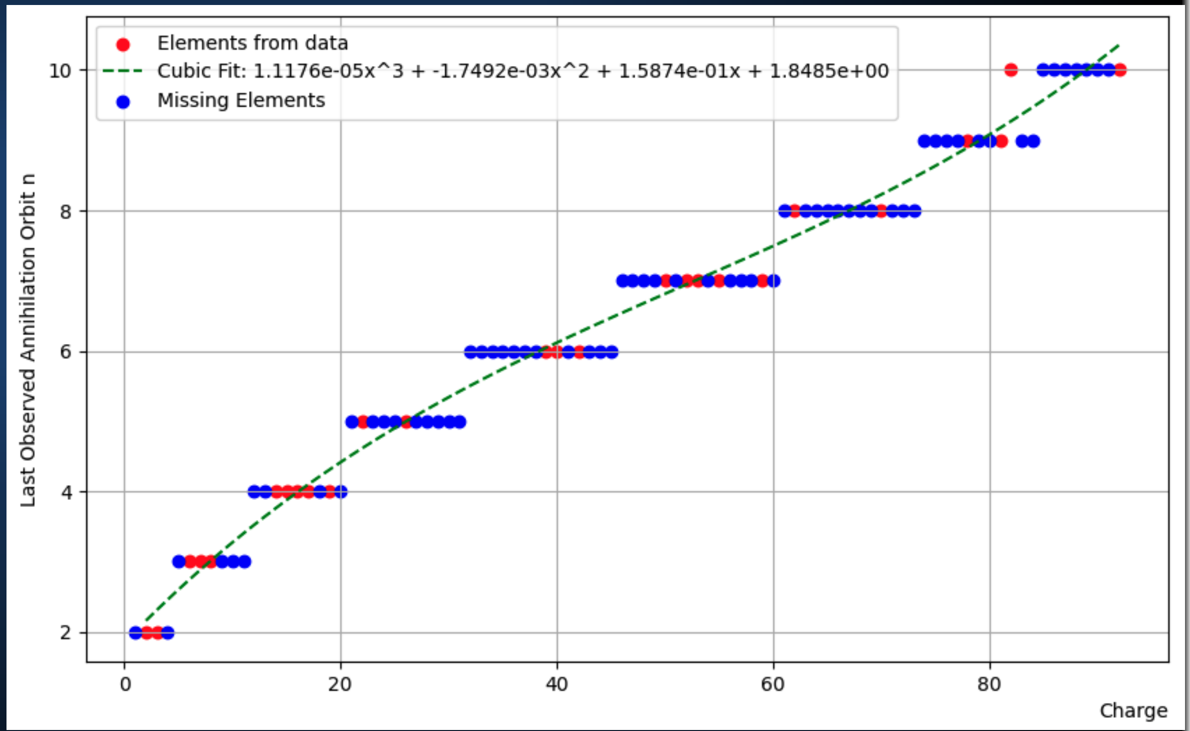


Antiprotons in INCL
Hypotheses – ingredients

At rest - Position of annihilation

- pbar
  Captured in a high Bohr orbit
  Cascades toward the nucleus
  Stops/annihilates at a given « n »

- Determination of « n »
  (fits from exp. Data)



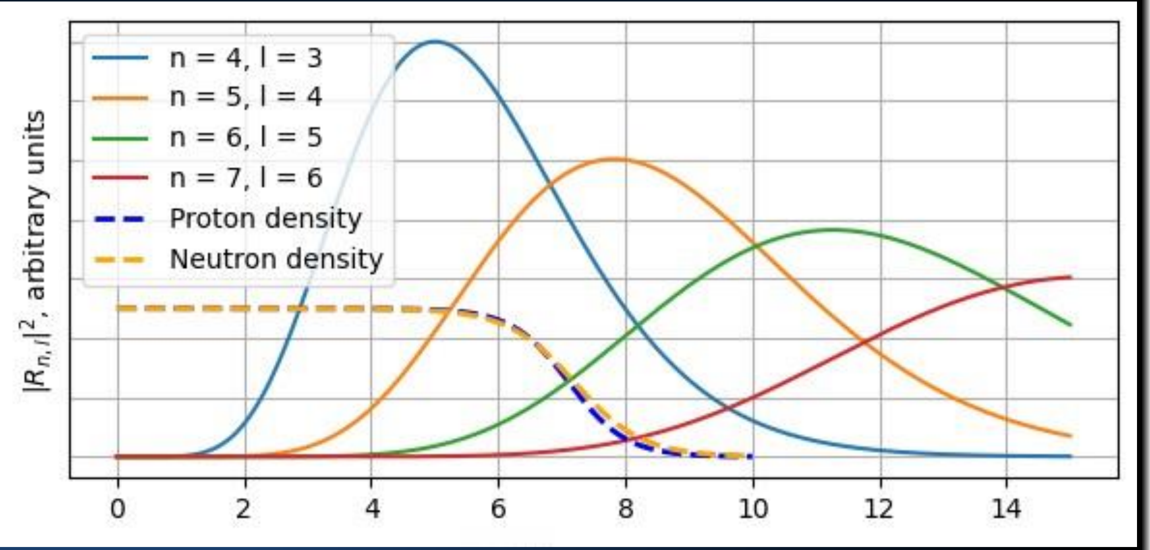
Antiprotons in INCL
Hypotheses – ingredients

At rest - Position of annihilation

- pbar
  Captured in a high Bohr orbit
  Cascades toward the nucleus
  Stops/annihilates at a given « n »

- Determination of « n »
  (fits from exp. Data)

- Position of annihiliation
→ When overlap of nuclear density
  and antiprotonic radial density



$$P_{neutronic}(r) = N_{nl} \times \rho_n \times r^2 \times |R_{n,l}|^2$$

$$|R_{n,l=n-1}| = ((2n)!)^{\frac{1}{2}} \left(\frac{2}{na}\right)^{\frac{3}{2}} \left(\frac{2r}{na}\right)^{(n-1)} \exp\left(\frac{-r}{na}\right)$$

$$N_{nl} = \frac{2}{n^2}\sqrt{\frac{(n-l-1)!}{((n+l)!)^3}} \quad \text{(a is the Bohr radius)}$$

Antiprotons in INCL
Hypotheses – ingredients

At rest - Final states

- In INCL we consider only π, η, ω and K (ρ goes directly to decay products)
- Kaon frequency is put at 5%
  - 2 old values 6.82 +/- 0.25 % and 4.74 +/- 0.22 %
  - « Recent » one 5.4 +/- 1.7 %
- Final states with π, η, ω taken from
  - E.S. Golubeva et al.
    Nuclear Physics A 537 (1992), 393–417.

  and with K from
  - Eberhard Klempt et al.
    Physics Reports 413 (2005), 197–317.

Channel	Probability (%)
$\eta\eta$	0.01 (1)
$\eta\omega$	0.34 (1)
$\omega\omega$	1.57 (1)
$\pi^+\pi^-$	0.40 (1)
$\pi^0\pi^0$	0.02 (1)
$\pi^+\rho^-$	1.52 (1)
$\pi^-\rho^+$	1.52 (1)
$\pi^0\rho^0$	1.57 (1)
$\rho^-\rho^+$	3.37 (2)
$\rho^0\rho^0$	0.67 (1)

Example Of Final States

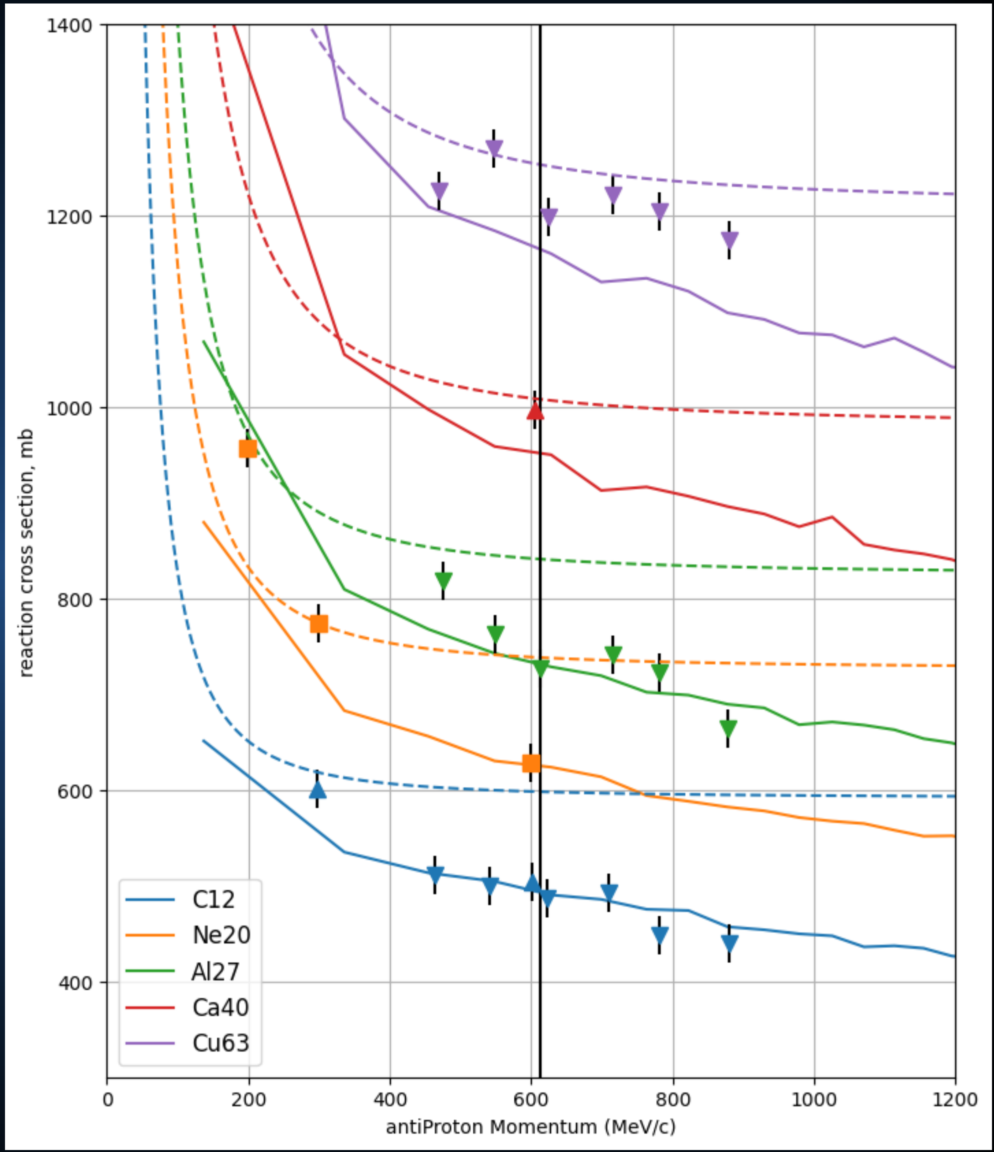
LEXAP 2024

Reaction Cross section

Solid lines: INCL calculations

Dashed curves: at rest normalization

$$\sigma_{reac} = \pi R^2 \left(1 + \frac{Ze^2(m_{\bar{p}} + M_{target})}{4\pi\epsilon_0 E_{kin} R M_{target}}\right)$$



Antiprotons in INCL
Results

Multiplicities p to ^{4}He, even beyond (comparisons to FLUKA, FTF)

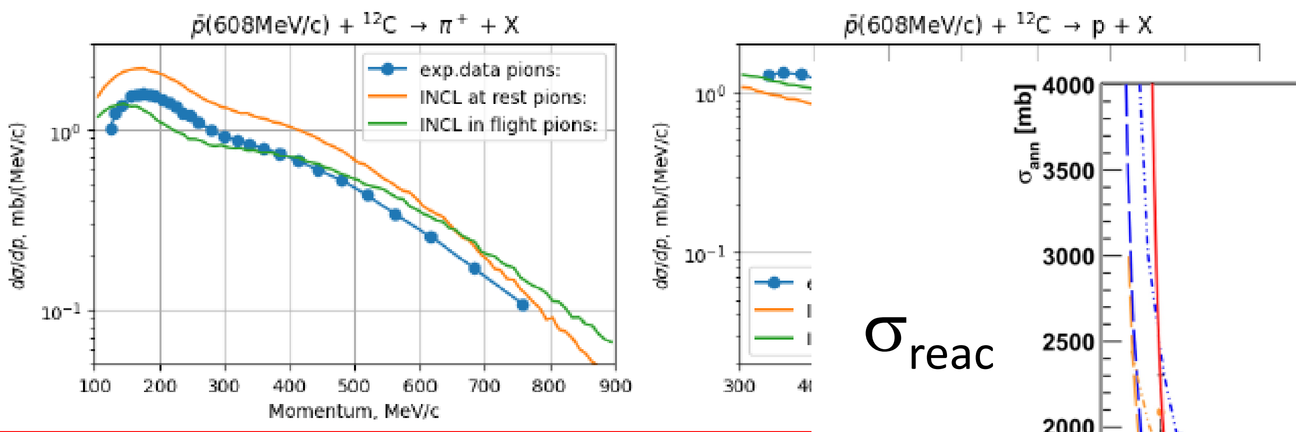
Table 5.4: Particle multiplicities for a given energy range after antiproton annihilation. The top value in each cell is taken from [Mar+88], statistical error in superscript, while systematic is subscript, error values are given with respect to the last digit (e.g. $74.2^{\pm 3}_{\pm 38} = 74.2^{\pm 0.3}_{\pm 3.8}$). The second value is the INCL, the red is FTF and the blue is FLUKA. The FLUKA and FTF results were kindly provided by Angela Gligorova (Stefan Meyer Institute).

range(MeV)	C12	Ca40	Cu63	Mo92	Mo98	U238
p (6-18)	$23.3^{\pm 2}_{\pm 18}$ 21.2 3.0 18.3	$74.2^{\pm 3}_{\pm 38}$ 122.2 6.7 30.2	$94.5^{\pm 4}_{\pm 78}$ 115.3	$127.2^{\pm 4}_{\pm 58}$ 155.6	$124.3^{\pm 3}_{\pm 64}$ 98.5	$76.6^{\pm 3}_{\pm 240}$ 34.9
d (8-24)	$9.3^{\pm 1}_{\pm 7}$ 19.9 0.0 13.1	$18.1^{\pm 2}_{\pm 9}$ 25.6 0.0 19.1	$28.0^{\pm 2}_{\pm 23}$ 31.0	$29.0^{\pm 2}_{\pm 13}$ 34.1	$30.4^{\pm 2}_{\pm 15}$ 29.9	$31.3^{\pm 2}_{\pm 99}$ 14.9
t (11-29)	$4.5^{\pm 1}_{\pm 3}$ 5.4 0.0 5.0	$5.7^{\pm 1}_{\pm 3}$ 5.0 0.0 8.1	$9.9^{\pm 1}_{\pm 8}$ 8.4	$11.8^{\pm 1}_{\pm 5}$ 8.7	$12.7^{\pm 1}_{\pm 7}$ 10.6	$18.8^{\pm 2}_{\pm 59}$ 12.1
^{3}He (30-70)	$1.72^{\pm 4}_{\pm 13}$ 1.74 0.0 2.0	$2.22^{\pm 5}_{\pm 12}$ 1.59 0.1 0.2	$2.60^{\pm 6}_{\pm 21}$ 1.62	$2.33^{\pm 5}_{\pm 11}$ 1.58	$2.06^{\pm 4}_{\pm 10}$ 1.25	$2.66^{\pm 6}_{\pm 84}$ 1.03
^{4}He (30-70)	$1.14^{\pm 3}_{\pm 9}$ 1.32 12.0 2.5	$2.18^{\pm 5}_{\pm 11}$ 2.67 4.0 1.6	$3.25^{\pm 7}_{\pm 26}$ 4.04	$3.78^{\pm 6}_{\pm 17}$ 4.69	$3.69^{\pm 6}_{\pm 17}$ 4.57	$5.94^{\pm 9}_{\pm 190}$ 7.66
^{6}He (39-89)	$0.025^{\pm 5}_{\pm 2}$ 0.022	$0.045^{\pm 7}_{\pm 3}$ 0.046	$0.048^{\pm 8}_{\pm 4}$ 0.083	$0.061^{\pm 8}_{\pm 3}$ 0.077	$0.060^{\pm 8}_{\pm 3}$ 0.111	$0.150^{\pm 20}_{\pm 50}$ 0.194
^{8}He (44-90)	$0.0041^{\pm 18}_{\pm 3}$ 0.0	$0.014^{\pm 4}_{\pm 1}$ 0.004	$0.0094^{\pm 36}_{\pm 8}$ 0.017	$0.011^{\pm 3}_{\pm 1}$ 0.021	$0.013^{\pm 4}_{\pm 1}$ 0.036	$0.041^{\pm 8}_{\pm 13}$ 0.088
Li (61-96)	$0.017^{\pm 4}_{\pm 2}$ 0.003	$0.075^{\pm 9}_{\pm 4}$ 0.022	$0.058^{\pm 9}_{\pm 5}$ 0.051	$0.086^{\pm 9}_{\pm 4}$ 0.054	$0.083^{\pm 9}_{\pm 4}$ 0.067	$0.180^{\pm 16}_{\pm 60}$ 0.120

INCL is clearly competitive

Antiprotons in INCL
Results

Spectra π^+ & p



Carbon

π^+ over and p under…!?

Not really…

σ_{reac}

pbar+C

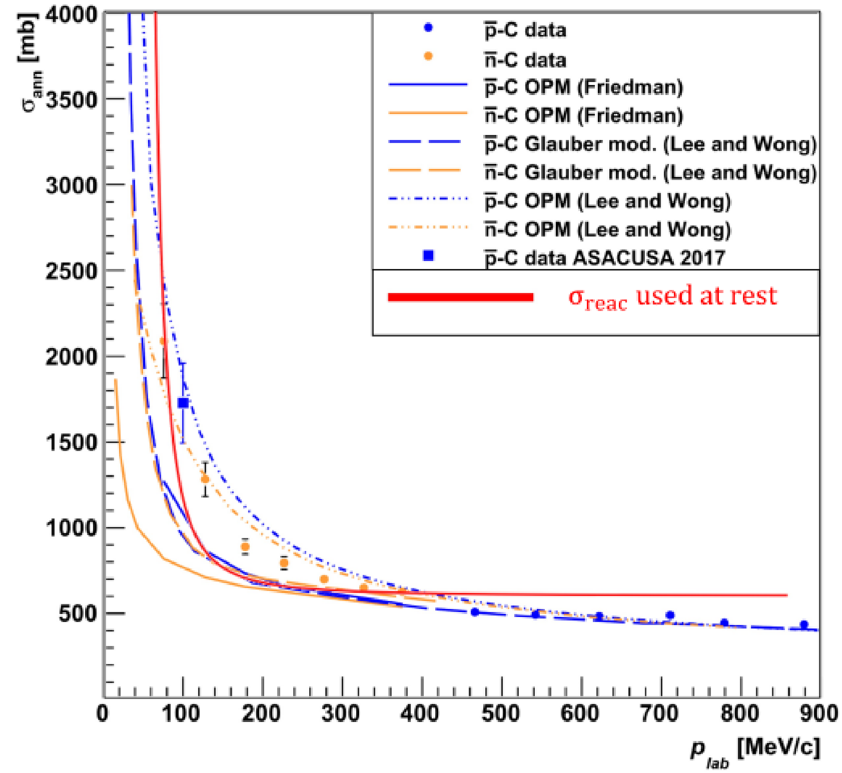


Figure 5.6: Antinucleon σ_{reac} at low energies on carbon. In orange the antineutron values, in blue those for antiproton. The points are the experimental data. The continuous lines represent the calculations with the optical potential model. The dashed lines are from the calculations with the extended Glauber model. The dotted-dashed lines are preliminary calculations obtained by means of a phenomenological optical model whose parameters are tuned to reproduce the N-nucleus annihilation data. Red line is the formula used in INCL from Ref.[Bia+11]. The original plot is taken from Ref.[Agh+18].